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14. ABSTRACT

Pursuing evasive prey, avoiding collisions with obstacles, and coordinating one's position in a group (formation) are some of the most important sensorimotor tasks that animals must perform. When studied in isolation, best-fit control laws can be dramatically different, but in an animal brain these behaviors are likely to be implemented by a small number of simultaneously-active and coordinating brain areas that work together to form a flexible amorphous behavior that can dynamically emphasize one or more subgoals. In this proposal, we seek to unify a number of different task-dependent control laws at multiple levels of abstraction from theoretical equations of control down to known neural substrates. Through carefully-chosen physical implementations (custom Neuromorphic VLSI and robotics) we will apply important practical constraints that can lead to deeper insight into how and why efficient, real-time systems exhibit certain behavior. Using the echolocating bat as a model system, we seek to unify prey pursuit control laws with formation control and collision avoidance, and to understand the theoretical consequences of stochastic sensory data and delays in the system. To support this work, our budget will cover the training of graduate students in the Controls area and the Microelectronics area, the submission of VLSI designs for fabrication through the MOSIS fabrication service, and the construction of robot and sonar testbeds for closed-loop behavioral experiments.

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Final Report for AFOSR # FA95500710446
Timothy Horiuchi; University of Maryland, College Park

This document provides a summary of the research supported by this award in the laboratories of Timothy K. Horiuchi and P. S. Krishnaprasad and identifies portions of the work that are collaborative or where our work is inspired by the other.

In the Horiuchi laboratory with support from AFOSR under the grant FA95500710446, a) we completed our testing and publication of our 1-D Openspace Collision Avoidance chip (Horiuchi, 2009), b) we completed our demonstration of 2D (elevation/azimuth) localization using an artificial bat head and an ultrasonic cochlea with feature-extracting spiking neurons (Abdalla and Horiuchi, 2009), (c) we completed and published a description of an initial prototype of a spiking neural network model of the head-direction-cell system used in rotational odometry for navigation (Massoud and Horiuchi, 2010), (d) we tested and published our initial work on using synaptic conductances to estimate sound azimuth based on interaural intensity differences (Horiuchi et al., 2009), (e) we have submitted for chip-fabrication, a 2D odometry system for mobile robotics based on the “grid and place cell” system found in the rat, f) we have developed a neurally-inspired network for episodic memory encoding to support the use of sensory inputs in a future spatial navigation system, and g) we have initiated a pilot study in the use of a wireless microphone telemetry system in analyzing the spectrotemporal properties of the vocalization sequence as a bat flies through an insect capture behavior.

The work of P. S. Krishnaprasad with support from AFOSR under the grant FA95500710446 and earlier awards, has resulted in a variety of advances including: (a) models and control laws for formations of unmanned aerial vehicles (UAVs) (Justh and Krishnaprasad 2002, 2004); (b) classification and stability analysis of formations in 2 and 3 dimensions (Justh and Krishnaprasad 2004, 2005); (c) models and control laws for individual pursuit behavior that are candidates for representing behavior in flocks (Justh and Krishnaprasad 2005, 2006, Reddy et. al. 2006, 2007); (d) collision avoidance strategies based on such models (Zhang et. al. 2004a, 2004b, 2010); (e) optimization-based methods to solve inverse problems of extracting control laws from empirical trajectory data (Reddy 2007); (f) biological evidence for pursuit control laws in prey-capture behavior by echolocating bats, in joint work with Cynthia Moss and Timothy Horiuchi (Ghose et. al. 2006, Chen et. al. 2010); (g) empirical investigation of these advances through applications in robotics (joint work with Horiuchi); and (h) comparison of different pursuit strategies using evolutionary games (Wei et. al. 2009).

Cochlear chip / spectral differencing system (Horiuchi – (a))

To support our ongoing work in modeling the use of the head-related-transfer-function in bat echolocation, an artificial bat head was designed and fabricated using a 3D printer and an ultrasonic cochlea-like filter bank with 16 channels has been designed. The cochlear channels have moderate quality (Q) factor and 128 spiking neurons convert these filter signals into spike trains. A two dimensional address-event arbiter is used to transmit these spikes off of the chip. In this work we have demonstrated that the population of spiking neurons can be decoded to estimate azimuth and elevation of ultrasonic chirps. This chip was fabricated in a commercially available 0.5 μm CMOS process and consumes 0.32mW. Early results from the chips have been presented in conference paper form (Abdalla and Horiuchi, 2008.)

In early 2009, two new feature-detection chips were fabricated to perform simple spectral analysis on the spikes from each cochlea and interaural level differences (between cochleae). These chips implemented simulation-validated (in MATLAB) feature extraction and the encoding of different directions. Under the restrictive assumptions of fixed intensity, full-spectrum ultrasonic chirps from different directions, we were able to demonstrate perfect localization (identified 703 different directions: 5 degrees resolution in elevation and 7.5 degrees in azimuth) under ideal conditions. In this proof of concept approach, we utilized binary-output feature detectors that operating on analog signals provided from the cochlea. Due to the graduation of the student working on this project, our journal paper on these results was delayed, but we now anticipate submission of these results by the end of 2010.

The head-direction-cell system spiking network chip (Horiuchi – (b))

The head-direction-cell system (HDS) is a group of neurons thought to be part of the circuitry responsible for spatial navigation in mammals. We have designed, fabricated, and are now testing a neuromorphic VLSI chip that implements a spike-based, attractor network model for the HDS that serves as the representation and memory of current estimates of head direction in world coordinates. We have demonstrated adjustable speed rotation of the bump of activity around the ring and have performed an analysis of the problems related to transistor fabrication mismatch. This estimate of head orientation provides a foundation for rotational odometry capabilities. We have demonstrated that the angular velocity integration works smoothly and with manageable nonlinearities. The chip was fabricated in a commercially-available 0.5 μm CMOS fabrication process and consumes approximately 86μW with a 5V supply.

To implement the rotation of activity in a manner that is linear with a rotational velocity signal, we have employed a little-used technique of disinhibition to "gate" the velocity signal to the appropriate set of neurons. We have published a short conference paper on early results from the chip (Massoud and Horiuchi, 2009) and we have published a longer, more comprehensive version of the results in Transactions in Circuits and Systems I (Massoud and Horiuchi, 2010).

Modeling conductance synapses, neurons, and computation (Horiuchi – (c))

We have been developing the conductance synapse/neuron for use in modeling the lateral superior olive (LSO) neurons which can take particular advantage of the computation performed by conductance-based synapses. Unlike traditional integrate-and-fire neuron computations, the conductance-based computation appears in the firing output as a ratio operation, which is appropriate for the computation that the LSO must perform in determining the interaural-level difference used in horizontal sound localization.

In late 2008, we successfully demonstrated the use of our conductance-based synapse to calculate the ratio of left and right intensities from a sonar system to implement the level comparison computation occurring in the lateral superior olive of the mammalian auditory system. This is documented in the conference paper in the references list below (Horiuchi et al., 2009). A larger chip that utilizes an array of these circuits for a fully-functional system is in development currently.

In a related project, we are optimizing a circuit that produces an alpha function current that will drive the conductance synapse described above. The alpha function circuit is important in providing milliseconds of current following the communication of a spike (in our address-event system, the duration is as short as 100 ns) and most importantly, it provides linearly summating currents. The linearly summating property is critical for using the synapse circuit to operate as a "virtual synaptic array" where the one circuit receives all spikes destined for the post-synaptic neuron regardless of source. Particularly in computational scenarios where synchronous inputs are important, this synapse circuit must properly act as if there were N synapse circuits in parallel. A chip design has been submitted for fabrication and is expected to return for testing in December.

A Two-Dimensional Odometry System (Horiuchi – (d))

As the next step (past the head-direction cell system) in our spatial navigation efforts, we are developing a neuromorphic analog VLSI-based model of the grid-cell and place-cell systems for translational odometry. As a brief summary, from experiments in rats, a particular sheet of grid-cells is thought to be interconnected such that it naturally produces a hexagonal grid pattern of activity that is able to slide across the sheet in response to translation of the animal through the world. This motion is expected to be in allocentric (world) coordinates and by using multiple sheets with different spatiotemporal frequencies of movement, like the individual digits of a car odometer, a locally unique pattern results at each location. A place cell is assumed to read the multi-scale grid cell population and respond to specific patterns of activation (i.e., responding to unique locations).

At this point in the project, we have performed spiking neuron simulations that effectively mimic the head-direction cell system projection kernel in two dimensions, however, due to the desire to simulate a high-resolution system at multiple scales, a self-contained routing system (as opposed to the address-event routing-based scheme used for the head-direction cell system) using analog current-mode calculations will be used. We have developed an analog circuit that produces a 2D hexagonal grid pattern of activity that can be translated on the sheet of "neurons". A 20x20 grid of these circuit elements is out for fabrication and due to vendor delays it is now expected in January 2011.

Episodic Memory and Recognition for Spatial Navigation (Horiuchi – (e))

As a complementary project to the rotational and translational odometry, we are developing an episodic memory for echolocation spatial patterns that can recognize sonar scenes combined with behavioral and internal states that serve as a larger context for memories. These models have a resemblance to similar networks proposed by adaptive resonance theory. We are currently in the algorithmic development stage, but have begun circuit designs that utilize a floating-gate memory synaptic array.

The episodic memory uses a two stage neural network: a feature-encoding layer and a competitive memory layer. For an episodic memory, each input pattern is expected to be unique and needs to be encoded efficiently with a minimum number of features. To accomplish this, we employ a training procedure where the network repeatedly experiences pattern examples from the environment and finds a feature encoding that maximizes the variance of the feature encoding layer across the ensemble. We use the "wake-sleep" training procedure to find these features. The second layer takes a "snapshot" of the feature layer. By ensuring that only one neuron is active in the second layer, only that neuron will learn the pattern of activity present at the output of the feature layer. If a pattern has been memorized before, the neuron that encoded that pattern will fire strongly and quickly, winning the competition easily. If no neurons have memorized that pattern, then no neuron will win immediately, indicating that there was no match. If no neuron wins, then a layer of "boost" neurons will soon begin to activate the memory layer, pushing the neuron with the closest match to eventually win. This will then trigger that neuron to memorize the pattern, erasing any previous memories on that neuron.

Analysis of Bat Echolocation Vocalizations: clustering algorithms (Horiuchi – (g))

As a beginning step towards determining if there is evidence that the echolocating bat's (big brown bat) navigation system operates by switching between different modes of operation (search, collision avoidance, approach, capture), we are investigating some techniques for comparing individual vocalizations during a capture trial to determine if the vocalizations fall into clusters that correspond to the particular behavioral it is performing at a particular time. We are currently using a spectrogram dot-product comparison followed by the Laplacian Eigenmaps technique to find natural clustering. The initial conclusion is that there ***are*** clusters of vocalizations that are used for specific behaviors. We are working with Prof. Cynthia Moss' lab to design new experiments that will provide more vocalizations for us to analyze. In particular, vocalizations during the landing have surprised us in their distinction from all other vocalizations.

Multi-Agent Systems (Krishnaprasad)

Further progress in control of networks of agents has been made through collaborations with graduate students Matteo Mischiati and Kevin Galloway, and Dr. Eric Justh of the Naval Research Laboratory. Specific items of interest include mutual motion camouflage (Mischiati and Krishnaprasad 2010a, 2010b), cyclic pursuit in 3 dimensions (Galloway, Justh and Krishnaprasad 2010) and optimal control of single and multi-agent systems with symmetries (Justh and Krishnaprasad 2010a, 2010b).

Under a short-term post-doctoral appointment during the period March 2010- September 2010, Bijan Afsari (who received his Ph.D. in applied mathematics under the supervision of P. S. Krishnaprasad and Karsten Grove in December 2009) made contributions to pursuit problems on manifolds (Afsari 2009, 2010) associated to the computation of averages on Riemannian manifolds. Afsari was partially supported under the AFOSR grant FA95500710446.

Additional support for the work of Krishnaprasad and his students has been obtained from the Army Research Office under ARO grant W911NF0610325, and from the ODDR&E MURI2007 Program Grant N000140710734, through the Office of Naval Research.

We describe briefly selected highlights of the work mentioned above.

Constant Bearing Cyclic Pursuit: Among different strategies for collective behavior in nature and in engineering, one based on motion under a cyclic directed graph of pursuit interactions, for prescribed constant bearing (CB) between each agent and its target of pursuit appears promising. Feedback control laws to execute such a strategy in two and three dimensions have been developed in collaboration with Kevin Galloway and Eric Justh. Nonlinear dynamics on associated shape spaces have been derived and partially analyzed in the joint work of Galloway, Justh and Krishnaprasad. Stability results for special solutions (relative equilibria, self-similar shapes) have been explored. This work has applications to synthesis of collective behavior among unmanned aerial vehicles engaged in such Air Force relevant missions as search-and-rescue, and surveillance.

Mutual Motion Camouflage Pursuit: The concept of motion camouflage (MC), first explored in the study of visual insects has been further investigated from mathematical perspectives, including the development of feedback laws when a pair of agents is engaged in mutual motion camouflage (MMC) by implementing in a symmetrical manner the control laws first identified by Justh and Krishnaprasad (2006). In the work of Mischiati and Krishnaprasad (2010a), nonlinear dynamics and conservation laws for this problem have been worked out in planar case, and more recently extended to three dimensions (Mischiati and Krishnaprasad 2010b). This work has direct relevance to the problem of cooperative sensing coverage with a small collective of agents.

Optimal Control: The occurrence of explicitly solvable optimal control problems is of interest in a variety of contexts of importance to control design. In the work of Justh and Krishnaprasad (2010a, 2010b) classes of such problems on the Euclidean group have been investigated, leading to open loop control laws described by elliptic functions of Jacobi. The occurrence of such control laws in mathematical models of collective behavior has been demonstrated in (Justh and Krishnaprasad 2010b). This set of ideas is of interest in establishing variational principles for collective behavior, a subject of fundamental interest. They are also relevant to the reconstruction of trajectories from sampled empirical data.

Biological Implications: In the Ph.D. work of Chen Chiu under the supervision of Cynthia Moss, foraging and flight behavior of echolocating bats were quantitatively analyzed in a study of paired big brown bats, Eptesicus fuscus, competing for a single food item in a large laboratory flight room (Chen et. al, 2010). Using measurements of their sonar beam patterns and recordings of flight paths with two high-speed cameras, it was shown that bats remained in nearly classical pursuit (CP) states when one bat is following another bat, i.e. a follower bat maintained direction of flight aligned with the line of sight between bats. Bats in the trailing position throughout a trial were more successful in accessing the prey. This work helped show that in nature distinct pursuit strategies are exploited to suit distinct purposes (e.g. Constant absolute target direction pursuit (CATD) as in Ghose et. al. (2006) to seek evasive prey vs. CP in foraging competition between conspecifics). The computational tools developed by Krishnaprasad and his student P. V. Reddy were used in this analysis.

New Directions: P. S. Krishnaprasad initiated with Andrea Cavagna of the Institute for Complex Systems (Rome, Italy) a new collaborative program of research in natural flocks and swarms (of birds and insects) aimed at discerning the underlying principles, working out models and algorithms to create quantitative support to the extracted principles, and exploiting the resulting understanding, as codified in models and algorithms, for the purpose of design, implementation and verification of robust, distributed, cooperative, survivable control systems for swarms of autonomous robots. Observations such as the topological character of the interaction in flocks of starlings *Sturnus vulgaris* serve as signposts for this purpose (Ballerini et. al. 2008a). Morphology and organization of sensory substrate in nature may guide similar design considerations in engineering – the possibility that in starlings the placement of eyes in the head may be a significant factor (Cavagna and Giardina 2008). How (visual, auditory, etc.) perception constrains and influences behavior is also of great interest.

The details and purpose of collective behavior in biology may vary according to species. Thus, in the case of starlings one sees graceful and agile flock behavior over a wide aerial expanse displaying nearly *laminar* individual trajectories (Ballerini et. al. 2008a, 2008b; Cavagna et. al. 2008b, 2008c). These appear in the context of predator avoidance, but the real purpose behind such flocking behavior is not understood. It is thus of great interest to do comparative studies across species. Unlike in former studies, such comparative analysis will be based on solid 3D empirical data that can now be gathered thanks to the novel methods in (Cavagna et. al. 2008a).

During summer 2009, Krishnaprasad and Cavagna collaborated with the assistance of two students, Raffaele Tavarone (undergraduate student in Physics at the University of Rome and member of Cavagna's research team) and Graham Alldredge (graduate student in Electrical Engineering at the University of Maryland). The purpose of this initial collaboration was to do *pilot data analysis* on starling data, using the perspective of models and steering laws developed in the AFOSR grant FA95500710446. Tavarone, as a visiting intern in the Intelligent Servosystems Laboratory (ISL), and Alldredge, analyzed large sets of trajectories (close to 600 in number from a single flocking event) gathered by Cavagna's group, using models and optimization methods (for extracting control signals) developed in ISL. These methods were originally developed by Krishnaprasad and his former student (Reddy 2007) to solve the corresponding inverse problem in the setting of bat prey capture behavior (Ghose et. al. 2006). The resulting database of steering control signals of starlings has been subject to initial statistical analysis to discern the presence of regularities in further support of the topological interaction hypothesis. Work in progress suggests that the models and algorithms developed under AFOSR support are ready to be further refined, and exploited for gaining deeper insight and advancing our knowledge of flocking/swarming behaviors in diverse species, with applications to engineered systems. This effort has led to a new AFOSR Grant (starting on June 1, 2010).

Recognitions received for the work supported by AFOSR:

P. S. Krishnaprasad delivered the Hendrik W. Bode Prize Lecture of the IEEE Control Systems Society in December 2007. The paper (Chen et. al. 2010) has been selected as the best paper of 2010 in The Journal of Experimental Biology. Kevin Galloway received a competitive L-3 Communications

Graduate Fellowship in September 2010. Krishnaprasad was invited to deliver colloquia and seminars on the work supported by AFOSR (see list below).

Selected Invited lectures by P. S. Krishnaprasad

Plenary Lecture, 3rd Northeast Control Workshop, University of Pennsylvania, Philadelphia: (May 16, 2007) "Geometry of Collective Steering"
Invited Lecture, 2nd Workshop on Swarming in Natural and Engineered Systems, University of Pennsylvania, Philadelphia: (May 16, 2007) "Pursuit Laws: theory and data"

Department of Mathematics Colloquium, Howard University, Washington D.C.: (November 16, 2007) "Pursuit and Cohesion: in Nature and by Design"

Hendrik W. Bode Prize Lecture (plenary), 46th IEEE Conference on Decision and Control, New Orleans: (December 14, 2007) "Pursuit and Cohesion: in Nature and by Design"

Inaugural Cymer Distinguished Lecture, Cymer Center for Control Systems and Dynamics, University of California, San Diego: (May 30, 2008) "Pursuit and Cohesion: from Biology to Autonomous Vehicles"

Invited Lecture, Mathematisches Forschunginstitut Oberwolfach, Germany: (July 26, 2008) "Pursuit and Cohesion"

Electrical Engineering Colloquium, University of California Los Angeles: (October 20, 2008) "Pursuit and Cohesion"

Invited Lecture, Third Workshop on Swarming in Natural and Engineered Systems, Block Island: (June 4, 2009) "Games and Dynamics"

GRASP Laboratory Colloquium, University of Pennsylvania: (March 26, 2010) "Geometry of Cyclic Pursuit"

CSCAMM Workshop on Nonlinear Dynamics of Networks 2010, University of Maryland, College Park: (April 6, 2010) "Pursuit and Collective Behavior"

Selected Invited Lectures by Timothy Horiuchi

ASME International Mechanical Engineering Congress and Exposition (IMECE07), Seattle, WA, Nov 12, 2007, Special Symposium on "The Fundamentals and Applications of Sensors and Sensing in Engineering and Biology – II", "A Neuromorphic VLSI-Based Bat Echolocation System" (Presentation only).

Univ. Maryland ECE Colloquium Series – November 30, 2007, "Bat Echolocation: Neuromorphic VLSI Modeling and Robotics".

Michigan State University – ECE Department – "Bat Echolocation: Neuromorphic VLSI Modeling and Robotics", April 24, 2008.

University of Virginia – Mechanical and Aerospace Engineering Dept – November 13, 2008, "Neuromorphic VLSI Modeling of the Echolocating Bat"

Uniformed Services University – Sept 9, 2010 - "Neuromorphic VLSI Modeling of the Echolocating Bat"

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